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Ashley Wiedower
University of Arkansas, Fayetteville

George Ondier
University of Arkansas, Fayetteville

Terry Siebenmorgen
University of Arkansas, Fayetteville

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Ashley Wiedower, George Ondier*†*, and Terry Siebenmorgen*§*

ABSTRACT

Rice moisture content (MC) must be reduced to approximately 12.5% MC to prevent spoilage during storage. Desiccants may provide an improved method for drying research-scale rice samples. This study investigated the effects of 1) rice mass to be dried, 2) placement method of silica gel packets in rice samples, 3) regeneration and re-use of the packets, 4) drying temperature, and 5) initial MC on the effectiveness of silica gel packets to dry rough rice samples to the desired 12.5% MC. Multiple masses (200, 500, and 1000 g) of long-grain rice samples were dried using three desiccant placement treatments: 1) intimate mixing (IM) of silica gel packets without agitation, 2) intimate mixing and agitation (IMA), and 3) surface placement (SP) of silica gel packets on top of the rice samples. The IMA treatments produced little variability in final MCs across the three masses used. The adsorptive capacity of silica gel packets in 200-g samples of two rice cultivars was measured. The adsorptive capacity varied from 26 to 35%. Effects of rice initial MC and drying temperature were measured by drying samples at initial MCs from 13 to 18% at 10°C, 20°C, and 30°C for eight days. Increased drying temperatures produced decreased final MCs for both cultivars, which became more pronounced as the initial MCs increased.

* Ashley Wiedower is a senior biological engineering major at the University of Arkansas.

† George Ondier is a Department of Food Science graduate assistant at the University of Arkansas.

§ Terry Siebenmorgen is a university professor in the Department of Food Science at the University of Arkansas.

MEET THE STUDENT-AUTHOR

Ashley Weidower

I graduated in May 2004 from Mount Saint Mary Academy in Little Rock, Ark., with an International Baccalaureate Diploma. After graduation I enrolled at the University of Arkansas with the intent of pursuing a degree in biological engineering. I was awarded the University Scholarship, Department of Biological Engineering Scholarship, and a General College of Engineering Scholarship. Throughout my college career, I have served as treasurer of Engineers without Borders, scholarship chair for Alpha Delta Pi Sorority, and as a mentor for the Society of Women Engineers.

My interest in food-related engineering applications began following a class I took through the Biological and Agricultural Engineering Department called bioreactor design. I was fascinated by the number of physical, chemical, and biological properties that must be considered when designing food-processing equipment. I received the opportunity to learn more about the food industry when I began a special problems project with Dr. Siebenmorgen in the Food Science Department in spring 2007. I have thoroughly enjoyed my research experience, and this opportunity has allowed me to develop my research and technical skills, which will prove beneficial in the future. I plan to enroll in the Department of Food Science graduate school in fall 2008, and one day, work as a food-processing engineer at a major food corporation.

INTRODUCTION

In the mid-South rice growing regions of the United States, rough rice is generally harvested at 14% to 22% moisture content (MC*) (Schluterman et al., 2004). Breeders and other rice scientists annually harvest large numbers of small rice samples from different cultivars and at varying MCs. To minimize microbial activity and respiration, and thus establish a safe storage environment, the rice MC must be reduced to less than 14% (Schroeder, 1963; Dillahunty et al., 2000).

Methods currently used for drying small rough rice samples involve exposure to air at low temperatures (< 40°C) and relative humidities (RHs) (<60%) until the desired final MC is attained. Higher drying temperatures, typical of those used in commercial driers, are reported to have a negative impact on grain quality, especially germination (Danziger et al., 1972), which makes these commercial methods unsuitable for drying research-scale samples (Aldis et al., 1980). Drying these samples in air-conditioned rooms often results in large variation in final MCs, which subsequently leads to variation in processing property measurements.

One possible solution to minimize final MC variation involves the use of desiccants. Desiccants have been used successfully to dry inshell pecans (Ghate and Chinnan, 1984). Yamaguchi and Kawasaki (1994) modeled two methods of drying rice with silica gel, a common desiccant that has potential in grain dying. Use of solar-regenerated silica gel to dehumidify air was found to significantly reduce the drying duration for corn and milo (Aldis et al., 1980). Danziger et al. (1972) determined that corn dried with desiccated air increased germination rates. Desiccants have also been used to reduce MC of soybeans (Zhangyong et al., 2002), corn (Graham et al., 1983), wheat and oats (Sturton et al., 1983) to levels safe for storage.

Silica gel is inert, has a high absorbency, and can be regenerated easily using high temperatures (>100°C) without significant reduction in adsorptive capacity (Koh, 1977). Silica gel is available in various-sized, moisture-permeable packets that would be ideal for drying small samples of rough rice. Such packets offer excellent handling properties, reduce separation costs, and minimize the risk of product contamination.

To fully understand sorption drying of rough rice using silica gel, a thorough knowledge of the moisture transfer relationships between silica gel and rough rice is required. In particular, measuring the equilibrium MCs of rice and silica gel is critical because final MC, and not drying rate, is influenced by the silica gel-to-grain mass ratio (Sun and Woods, 1997). Information on the adsorptive capacity and the effect that repeated regeneration cycles have on silica gel effectiveness is also required to evaluate potential use of silica gel in rice drying (Ghate and Chinnan, 1984).

The goal of this study was to investigate an alternative to conventional air drying of research-scale rough rice samples. It was therefore important to determine the parameters and conditions that may alter adsorptive behavior of silica gel packets and to establish a set of guidelines for use of the packets. Objectives were to a) determine influence of the mass of rice dried and method of placement/mixing packets in rough rice samples on drying effectiveness, b) determine adsorptive capacities of new and regenerated silica gel packets in rough rice samples, and c) determine effect of drying temperature and initial rice MC on achieving a desired, final MC of 12.5%.

MATERIALS AND METHODS

The first objective was to determine optimal desiccant placement, sample treatment, and rice mass to be used to maximize drying effectiveness of silica gel packets. The second objective sought to quantify the mass of desiccant required to dry a rice sample to a target MC of 12.5% and to determine if silica gel packets could be regenerated without a reduction in adsorptive capacity. The final experiment investigated effects of air temperature and initial rice MC on final MC of rice samples.

Rice sample preparation. 'Wells' and 'CL730' rice cultivars (long-grains) harvested in 2007 from Stuttgart, Ark. at 17.1% and 20.2% MC, respectively, were cleaned using a dockage tester (XT4, Carter-Day Co., Minneapolis, Minn.) and stored in covered, 32-gallon plastic bins at 5°C for 12 wks. Bulk sample MCs were determined after harvesting and before storage by drying duplicate 20-g rice samples in a convection oven (1370 FM, Sheldon Inc., Cornelius, Ore.) maintained at 130°C for 24 h (Jindal and Siebenmorgen, 1987). Before each test, the samples were removed from cold storage and equilibrated to room temperature while in plastic bags to prevent condensation onto the samples.

Rice sample treatment and desiccant placement. Three drying methods were investigated: intimate mixing (IM) of rough rice and silica gel packets without agitation, intimate mixing and agitation (IMA) of the drying container at 24-h intervals over the drying duration, and surface placement (SP) of silica gel packets on top of the rice samples. Effect of rough rice sample mass on each drying method was also investigated. Samples of 'CL730' rice, initially at 20.7%, were divided into 200-, 500-, and 1000-g denominations and dried using 5-g silica gel packets by each of the three above methods (Fig. 1). Each rice sample, with its corresponding mass of desiccant, was placed inside a re-sealable (Ziploc) plastic bag.

To determine the mass of silica gel packets needed to dry these samples to the target MC of 12.5%, the adsorptive capacity of the silica gel packets was estimated to be 25% (0.25 g of H_2O/1 g of silica gel). The mass of silica gel required was dependent on the mass and initial MC of the rice to be dried and was the same for each of the three drying methods. For instance, drying 200 g of rice from an initial MC of 20.7% to the desired 12.5% MC required the removal of 18.7 g of water (determined by mass balance). The mass of silica gel necessary was then determined by dividing the mass of water to be removed by the estimated adsorptive capacity of the packets. Given an estimated adsorptive capacity of 25%, 75 g of silica gel (18.7 g of H_2O/0.25 g H_2O/g silica gel) would be required to dry the rice samples to the desired final MC of 12.5%. Thus, fifteen 5-g packets and zero 1-g packets were used. In situations where the required silica gel mass was not evenly divisible by five, in which a fraction of a 5-g packet would be needed, a combination of 1- and 5-g packets was used to supply the required mass and thereby minimize the possibility of over- or under-drying the rice samples.

The IMA samples were mixed by manually shaking the plastic bags containing the rice samples and silica gel packets at 24-h intervals to improve air circulation, thus increasing the mass transfer rate from the rice kernels to the inter-particle air and subsequently to the silica gel packets. Theoretically, it was assumed that the silica gel-packet adsorptive capacity would be optimized and the drying rate maximized if the plastic bags containing the rice samples and silica gel packets were periodically agitated. The IM samples were not agitated except at the beginning of the experiment. The SP drying method comprised placing silica gel packets directly on top of the rice bulk; the samples were not agitated. All plastic bags remained sealed and were kept in a chamber maintained at 26°C for 8 d, after which the packet masses were measured using an analytical balance with an accuracy of ± 0.0001 g (EO1140, Ohaus Co., Zurich, Switzerland). The rice MCs were determined by the oven method previously described. The actual adsorptive capacities of the packets were determined as the mass percentage increase of the initial desiccant-packet mass.

Adsorptive capacities of new and regenerated silica gel packets. Silica gel adsorptive capacity (as indicated by the manufacturer) is usually based on exposure to a moisture-saturated environment and is typically expressed as mass of water adsorbed per mass of desiccant. Adsorptive capacity in closed samples of rough rice is expected to be lower due to resistance to moisture migration inside kernels. To determine the maximum adsorptive capacity of the silica gel packets, twenty 1- and 5-g silica gel packets (ten of each) were placed on a wire mesh in a closed metal container that was partially filled with water such that only moisture-saturated air came in contact with the silica gel packets. The packets were held in this saturated environment at 26°C for 8 d. The initial and final masses of each packet were measured as previously described, after which the packets were regenerated in a convection oven (1370 FM, Sheldon Inc., Cornelius, Ore.) at 130°C for 24 h. The regenerated packets were then re-exposed to the saturated environment for 8 d (Fig. 2). The exposure and regeneration procedure was repeated twice in order to establish the maximum adsorptive capacity of the new, once-, and twice-regenerated silica gel packets studied. The loss of effectiveness of the packets resulting from subsequent regeneration was determined by the reduction in the adsorptive capacity of the regenerated packets compared to the adsorptive capacity of the new packets. Each experiment was replicated.

As a means of estimating the actual adsorptive capacity of the silica gel packets in rough rice, a procedure was developed in which assumed adsorptive capacities ranging from 15 to 30% were used to calculate the mass of desiccant required to reduce rough rice samples to the desired 12.5% MC. After drying, a graph of the final rice MCs against the assumed adsorptive capacities was plotted, and a regression line was used to indicate the adsorptive capacity that corresponded to the desired 12.5% final rice MC (Fig. 4). Eight, 200-g samples (two replicates) each from 'CL730' and 'Wells' cultivars, initially at 20.2% and 17.1% MC, respectively, were dried using new 5-g packets (Fig. 2). The mass of desiccant placed in each sample was determined based on the assumed desiccant adsorptive capacities (15% to 30%) and the mass balance procedure previously described. The rough rice samples and silica gel packets were intimately mixed (IM) in plastic bags and kept in a chamber maintained at 26°C for 8 d. The mass of the silica gel packets and MCs of the rice samples were determined using the previously-described methods. The silica gel packets were regenerated in the same convection oven at 130°C for 24 h, and then re-used to dry a second batch of rough rice from the same initial MCs following the same procedure (Fig. 2). The regeneration and drying cycles were repeated twice.

Initial MC and temperature effects on final rice moisture content. Bulk rice samples from the 'CL730' and 'Wells' lots, initially at 20.2 and 17.1% MC, respectively, were conditioned in a chamber maintained at 26°C and 55% RH for varying durations to yield samples at the target initial MCs of 18%, 15%, and 13%. Duplicate 200-g samples from each cultivar and conditioned MC lot were then dried in plastic bags using 5-g silica gel packets in chambers maintained at 10°C, 20°C, or 30°C for 8 d (Fig. 3) to determine the influence of initial MC and drying temperature on final rough rice MC. For this experiment, the silica gel adsorptive capacity was estimated as 25%. The initial and final rice sample MCs were determined using the above oven method.

All statistical analyses, which included analysis of variance (ANOVA) and linear regression, were performed using JMP 7.0.1 (SAS Inst. Cary, NC).

RESULTS AND DISCUSSION

Rice sample treatment and desiccant placement. Based on results of a T-distribution analysis, the mass of rice dried produced significant effects (p-value < 0.05) on the silica-gel adsorptive capacities for the surface placement (SP) and the intimately mixed (IM) treatments. Significant differences (p-value 0.0146) for the SP treatment were found between the 500- and 1000-g samples, whereas there were no significant differences between the 200- and 500-g samples (Table. 1); adsorptive capacities of the 200-, 500-, and 1000-g samples were 25.5, 24.1, and 17.8%, respectively. This trend is attributed to reduced interaction between the silica gel packets and rough rice kernels, after a certain mass of rice was reached. By placing the silica gel packets on the surface of the rice bulk, the effective packet surface area in contact with the rice was reduced, thereby increasing the resistance to moisture migration from the kernels. This lack of direct interaction between the silica gel packets and rough rice kernels contributed to the slow rate of moisture diffusion into the silica gel packets, which became more evident as the mass of rice dried using this treatment increased.

Within the intimately mixed and agitated (IMA) samples, adsorptive capacities of the silica gel packets in the 200-, 500-, and 1000-g samples were not different (p-value >0.05), and therefore, mass of rice dried did not influence the resulting adsorptive capacities of the packets. The increased interaction between the rice kernels and desiccant packets due to the daily agitation with the IMA method minimized the effects of rice mass on the adsorptive capacities for this treatment.

Significant differences (p-value 0.0748) for the IM treatment were found between the 200- and 500-g samples, whereas there were no significant differences between the 200- and 1000-g samples or between the 500- or 1000-g samples. Adsorptive capacities for the

200-, 500-, and 1000-g samples were 26.3, 23.1, and 24.4%, respectively. Even though the desiccant packets were supposedly distributed evenly throughout the rice samples in the IM method, there may have been some incomplete mixing in the 500-g sample; this incomplete, initial mixing would be alleviated by the practice of daily agitating the samples in the IMA method.

Upon examining the final MC for each mass denomination and drying method, there was a consistent, inverse correlation between adsorptive capacity and final rice MC. Thus, the trends in final MC due to drying method and rice mass reflect that of the desiccant adsorptive capacity. The IM 200-g and the IMA 200-, 500-, and 1000-g rice samples were dried to MCs below the desired 12.5% (Table 1), which corresponds to the greater adsorptive capacities previously recorded in these samples (> 26%). These over-dried samples indicate that the mass of desiccant present in those samples was more than that required to reach the 12.5% target MC. Since the required desiccant mass is inversely proportional to the adsorptive capacity of the desiccant, the actual adsorptive capacity of these packets was effectively greater than the initially estimated value of 25%. This same trend is illustrated with the final MCs of the rice samples and adsorptive capacities of rice dried using the SP method, wherein the rough rice samples may have retained a greater amount of moisture due to less and non-uniform osmotic pressure developed within the plastic bag.

In summary, the average adsorptive capacity of the silica gel packets was dependent on the level of sorption interaction between the silica gel packets and rough rice. Intimately mixing and agitating the rice with the silica gel packets optimized the packets' adsorptive capacities due to increased interaction between the silica gel and the rice kernels. Surface placing the packets on the rice samples was the least efficient method of drying, yet with the 200-g masses, the SP method produced statistically similar adsorptive capacities as the other two methods, indicating that this method is suitable for small samples, but unsuitable for larger masses of rice. Comparing the IM and IMA methods showed some inconsistency was found in adsorptive capacities and final MCs if samples were not agitated. From a practical standpoint, little difference in final MCs was observed between the IM and IMA methods for the 200-g samples; for greater sample masses, periodic agitation may be needed to attain maximum drying.

Adsorptive capacities of new and regenerated silica gel packets. While there were no significant differences (p-value 0.7834) observed between the maximum adsorptive capacities of the new, once-, and twice-regenerated 1-g or 5-g silica gel packets exposed to an environment saturated with moisture, there was an apparent increase in the adsorptive capacities when regenerating the new desiccant packets for the first time; this increased capacity remained constant for the subsequent regeneration (Table 2). Due to opening and closing of the desiccant container in which the packets were stored, new packets were repeatedly exposed to moisture in the air, which may account for the greater initial mass of the new 5- and 1-g packets in comparison to the once-regenerated packets and the corresponding increased adsorptive capacities. Since the once- and twice-regenerated packets were both oven-dried to remove moisture adsorbed in the saturated environment, the initial desiccant masses of both treatments were equal. Consequently, the final average adsorptive capacities were also similar. This observation could have implications for the procedure used by practitioners since the regeneration process appears not to have an effect on the adsorptive capacities of silica gel packets. It is also important to note that while there were no statistical differences between the adsorptive capacities of the 1-g and 5-g packets, the 1-g packets were consistently lower than the capacities of the 5-g packets.

A regression analysis was used to determine the actual adsorptive capacity of the silica gel packets when drying rough rice (Fig. 4). Actual adsorptive capacity was determined as the value on the x-axis that corresponds to the desired 12.5% rice MC on the y-axis. The adsorptive capacity of the new silica gel packets needed to dry 'Wells' samples initially at 17.1% was greater (35.4%) than that required to dry 'CL730' samples initially at 20.2% MC (28.7%). Since both rice cultivars were exposed to the same drying temperature, the initial MC of the rice may account for the adsorptive capacity differences between the CL730 and Wells cultivars studied.

After these same silica gel packets were regenerated once, the adsorptive capacity from the regression analysis for the 'CL730' cultivar increased slightly from 28.7% to 30.2%, while the corresponding analysis for the 'Wells' cultivar produced a slight decrease in adsorptive capacity from 35.4% to 34.5% (Table 3). Adsorptive capacities of the twice-regenerated silica gel packets revealed a significant drop between the once- and twice-regenerated packet adsorptive capacities. The adsorptive capacity for twice-regenerated packets in the 'CL730' samples was considerably lower (26.5%) than the adsorptive capacities of the once-regenerated desiccants (30.2%), as were also the twice-regenerated and once-regenerated desiccant adsorptive capacities for the 'Wells' cultivar (30.9% and 34.5%, respectively).

An additional experiment and regression analysis were performed based on assumed adsorptive capacities ranging from 15 to 45% to better span the actual adsorptive capacity range of 25 to 35%. This analysis provided results (Table 3) similar to the initial regression analysis in that the adsorptive capacity of 'Wells' (33.7%) was greater than that of 'CL730' (26.5%). The adsorptive capacity values from this analysis were slightly less than initial new desiccant analysis values. This experimental verification, based on a range of adsorptive capacities from 15 to 45%, was performed several weeks after the initial experiment began. As previously discussed, due to opening and closing the desiccant storage container, desiccant packets were exposed to the surrounding air allowing the packets used in the 15 to 45% analysis to adsorb more moisture than those used in the 15 to 30% analysis. The inconsistent results of this experiment merit further testing.

Effect of initial MC and temperature on adsorptive capacity. The effects of initial MC and ambient temperature on the final MCs of samples from the two cultivars conditioned to various initial MCs are shown in Figure 5. Ambient temperature had a similar effect on the final MCs of both cultivars in that as the drying temperature increased, the final MCs decreased. The initial MC of a sample also affected its final MC. The difference between the final MCs of samples at the same initial MC and from the same cultivar increased as the initial MC increased. The final MCs for both cultivars were most likely determined by rice equilibrium MC trends in that as grain temperature increases, the equilibrium MC decreases, causing rice at higher drying temperatures to reach a lower final MC.

When comparing samples dried at the same temperature, the final MCs of the Wells samples were lower than those of the CL730 samples at similar initial MCs, which may be due to differences in the internal kernel matrices and constituents of each cultivar. These internal kernel differences were also believed to influence the final MCs in the previous section, which determined the actual adsorptive capacity of each cultivar.

In summary, as ambient temperature increased, the final MCs decreased for both cultivars, as would be expected due to equilibrium MC trends. Differences in final MCs associated with the drying temperatures became more pronounced as the initial MCs increased. The initial MCs, however, were not the sole determinant of the final MCs at a given temperature, indicating inherent differences in the final MCs associated with the cultivars. The practical ramification of this is that to achieve a 12.5% final MC, differences in adsorptive capacities may be required for various cultivars, or, if the same adsorptive capacity is used across cultivars, some inherent cultivar-to-cultivar variability in final MC may be expected.

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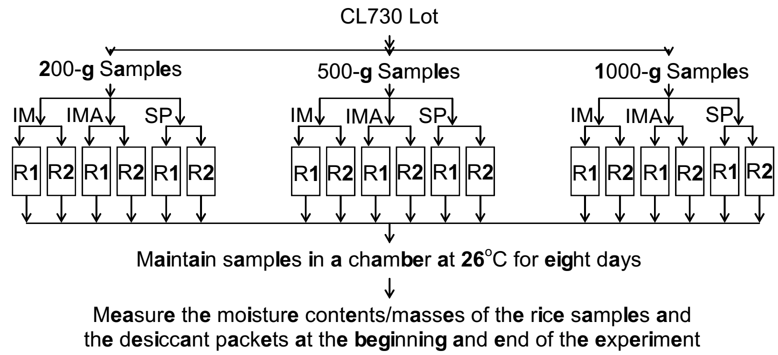

Fig. 1. Schematic of the experiment to determine effect of intimately mixing rice samples with silica gel packets (IM), intimately mixing with agitation (IMA) and surface placing (SP) packets above rice bulk, on adsorptive capacity of 5-g silica gel packets.

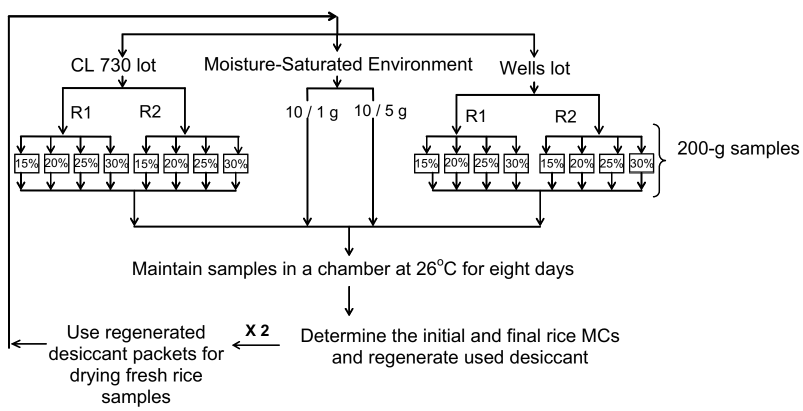

Fig. 2. Schematic of the experiment to determine adsorptive capacities of new and regenerated silica gel packets in an environment saturated with moisture and intimately mixed in rough rice using assumed adsorptive capacities of 15 to 30%.

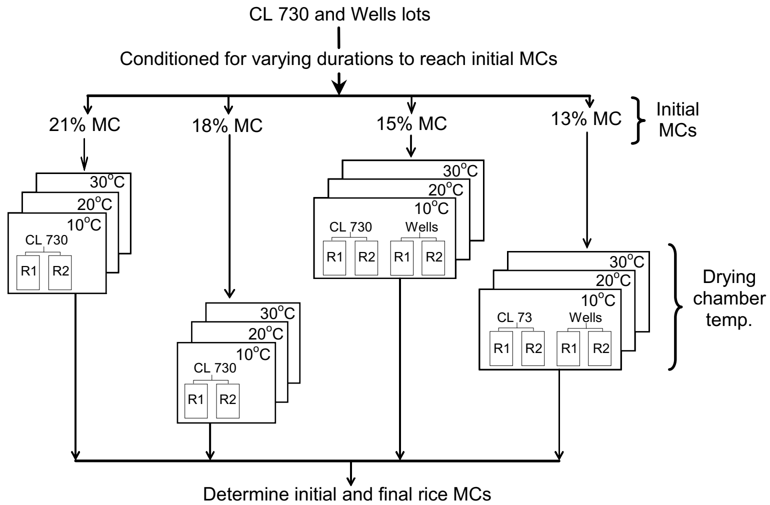

Fig. 3. Schematic of the experiment to determine effect of temperature and initial moisture content (MC) on final rice MC when drying Wells and CL730 rice samples using silica gel packets.

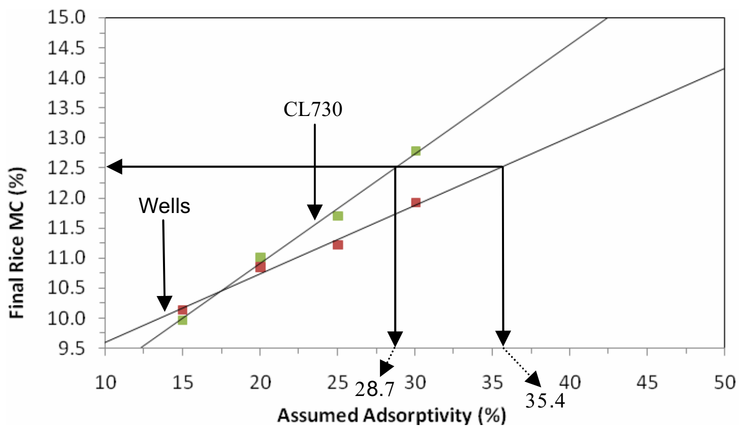

Fig. 4. Linear regression used to determine actual adsorptive capacity of new silica gel packets needed to dry intimately mixed rice samples of Wells and CL730, initially at 17.1 and 20.2% MC, respectively, to a desired 12.5% MC within a period of 8 d. Each data point represents an average of four measurements.

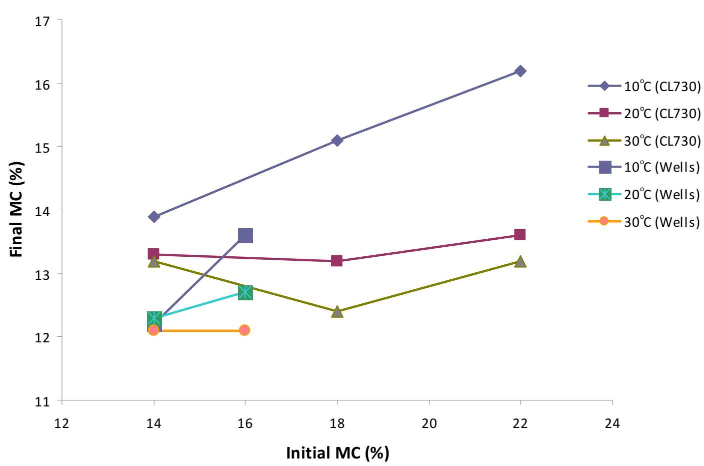

Fig. 5. Linear analysis evaluating effect of temperature on final moisture content (MC) of CL730 and Wells cultivars when conditioned to a given initial MC.

Table 1. Comparison of adsorptive capacities of silica gel packets and final rice moisture contents (MCs) as influenced by mass of rice dried and drying method. Initial adsorptive capacity of silica gel packets was estimated as 25%. Values not listed with the same letter are significantly different.

Drying Method	Rice Mass (g)	Initial Desiccant Mass (g)	Adsorptive Capacity (%)[b]	Final Rice MC (%)[c]
Intimately Mixed	200	72	26.3 (AB)	11.9 (BC)
Intimately Mixed	500	182	23.1 (C)	12.5 (E)
Intimately Mixed	1000	362	24.4 (BC)	12.4 (DE)
Intimately Mixed Agitated	200	72	27.8 (A)	11.6 (A)
Intimately Mixed Agitated	500	182	25.4 (ABC)	11.6 (AB)
Intimately Mixed Agitated	1000	362	26.4 (AB)	11.6 (A)
Surface Placement	200	72	25.5 (ABC)	12.2 (CD)
Surface Placement	500	182	24.1 (BC)	12.7 (E)
Surface Placement	1000	362	17.8 (D)	14.9 (F)

[b]Each adsorptive capacity observation is an average of two replicates (Fig. 1).
[c]Each final rice-moisture content observation is an average of four measurements. Duplicate oven MC determinations were made for each replicate (Fig. 1).

Table 2. Maximum adsorptive capacities of 1- and 5-g silica gel packets determined by exposing to a moisture-saturated environment for 8 d. Each observation is an average of ten measurements.

Number of Regenerations	Packet Size (g)	Average Mass of Silica Gel Packets (g)		Average Adsorptive Capacity (%)
		Initial Mass (g)	Final Mass (g)	
0	5	4.84	6.66	37.6
0	1	1.16	1.56	35.3
1	5	4.78	6.64	39.0
1	1	1.14	1.56	36.6
2	5	4.78	6.64	39.0
2	1	1.14	1.55	35.7

Table 3. Adsorptive capacities (%) for new, once-, and twice-regenerated desiccant packets from CL730 and Wells cultivars calculated from a linear regression of the final rice moisture content (MC) against assumed adsorptive capacities (15 to 0%) at the final rice MC of 12.5%.

	New desiccant packets[d]	Once-regenerated desiccant packets	Twice-regenerated desiccant packets	New desiccant packets[e]
CL730	28.7	30.2	26.5	26.5
Wells	35.4	34.5	30.9	33.7

[d]Values based on adsorptive capacities ranging from 15 to 30%.
[e]Values based on adsorptive capacities ranging from 15 to 45%.